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MICROWAVE PROBING OF ELECTRON DECAY IN A GAS DISCHARGE

by

Marland C. Gale

Scientific Report PIBMRI 977-61

for

Air Force Cambridge Research Laboratories
Office of Aerospace Research
Bedford, Massachusetts

Contract No. AF-19(604)-7216
Project No. 4619 Task No. 46191
January 18, 1963

MRI

POLYTECHNIC INSTITUTE OF BROOKLYN

MICROWAVE RESEARCH INSTITUTE
ELECTROPHYSICS DEPARTMENT

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ACKNOWLEDGMENT

The work described herein has been supported by the Electronics Research Directorate of the Air Force Cambridge Research Laboratories under Contract No. AF-19(604)-7216.

ABSTRACT

The electron density in a plasma can be determined by measuring the phase shift of a low-power microwave signal transmitted through the plasma. Measurement of the attenuation of the transmitted signal makes possible the determination of the electron-neutral particle collision frequency. Knowledge of the collision frequency in turn makes it possible to determine the electron density more accurately.

A method is described for determining the electron density and collision frequency in the afterglow of a pulsed discharge in hydrogen. The results indicate that the electron density does not decay exponentially, but that it decays more rapidly at first and less rapidly later. It is shown that this is probably due to the existence of a net negative charge in the center of the discharge tube, arising from sputtering of the cathode metal onto the walls of the tube, or to the presence of impurity atoms.

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INTRODUCTION

A plasma can be defined as a partly ionized gas which is macroscopically neutral. It is made up of electrons, positive and negative ions, and uncharged atoms and molecules, and in any sufficiently large volume* the numbers of positive and negative charges are equal. In laboratory plasmas the gas is generally contained in a discharge tube containing two electrodes, and an ionizing voltage is applied across the electrodes. When the pressure in the discharge tube is of the order of a few millimeters of mercury, an applied voltage produces a uniform glow throughout the tube, and the discharge is known as a " glow discharge." It is with this type of discharge that this report is concerned.

Use of a pulsed dc voltage makes it possible to achieve high instantaneous electron densities with low average power dissipation. The duration of the pulse is much smaller than the time between pulses. During the time the voltage is applied, the gas is partly ionized and becomes conducting, and the electron density builds up to its maximum value. In the afterglow region when the voltage is removed, the electrons gradually recombine with the positive ions, and the electron density slowly decays to zero.

The discharge tube used in the experiment is in the shape of a rectangular box. The electrodes, at opposite ends of the box, are made of 15/16 inch stainless steel plate, and their inside dimensions are 10.5 by 12.0 centimeters. The other four sides are constructed of 5/8 inch Pyrex glass. The length of the tube between electrodes is 18.95 centimeters.

The purpose of this study was to observe the decay process by using a microwave (Kband) probe and to find out if some information can be obtained about the electron distribution in the discharge tube.

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* By " sufficiently large volume" is meant any volume which is large compared to the cube of the Debye shielding distance, given by $h = (\varepsilon_o kT/2N_o e^2)^{\frac{1}{2}}$. In the cases considered, h is approximately .001 cm.

DETERMINATION OF ELECTRON DECAY RATE NEGLECTING COLLISIONS

It has been shown that the propagation constant γ for a plane wave transmitted through a plasma can be written as

$$\gamma^2 = -\mu_o \epsilon_o \omega^2 \epsilon' .$$

Setting $\gamma = \alpha + j\beta$, where α is the attenuation constant and β is the phase shift per unit length, one obtains

$$\alpha^2 - \beta^2 + 2j\alpha\beta = -\mu_o \epsilon_o \omega^2\left[1 - \left(\frac{\omega_p}{\omega}\right)^2 - j\left(\frac{\omega_p}{\omega}\right)^2 \frac{\nu}{\omega}\right],$$

where $\omega_p = (ne^2/m\epsilon_o)^{\frac{1}{2}}$ is the plasma angular frequency. If $(\nu/\omega)^2$ is neglected compared to 1, it is not difficult to solve for α and β. The results are

$$\left.\begin{aligned} \frac{\alpha}{\beta} &\approx \frac{1}{2c}\,\frac{(\omega_p/\omega)^2\ \nu/\omega}{\left[1-(\omega_p/\omega)^2\right]^{\frac{1}{2}}} \\ \frac{\beta}{\omega} &\approx \frac{1}{c}\left[1-(\omega_p/\omega)^2\right]^{\frac{1}{2}} \end{aligned}\right\} \tag{1}$$

Consequently, if a plane wave of known frequency is transmitted a known distance through a plasma and the resulting phase shift is measured, it should be possible to determine the electron density n. If the electron density were uniform throughout the plasma, the total phase shift would be equal to the product of the phase constant β and the transmission distance d. However, the quantity determined experimentally is the difference between the shift due to the plasma and that for the same path length in the absence of plasma; thus,

$$\phi = -\left(\beta - \frac{\omega}{c}\right)d = -\frac{\omega}{c}\left\{\left[1-\left(\frac{\omega_p}{\omega}\right)^2\right]^{\frac{1}{2}} - 1\right\}d,$$

where ϕ is the measured quantity. In the general case, the electron density is not uniform bur varies from point to point, and the experimental phase shift ϕ is given by

$$\phi = \frac{\omega d}{c} - \int_o^d \frac{\omega}{c}\left[1 - \frac{\omega^2 p(z)}{\omega^2}\right]^{\frac{1}{2}} dz. \tag{2}$$

Assume that the plasma radian frequency ω_p is given as a function of position and time by

$$\frac{\omega^2 p(z,t)}{\omega^2} = Z(z)\,T(t)\ .$$

Then equation (2) becomes

$$\phi = \frac{\omega d}{c} - \frac{\omega}{c} \int_0^d \left[1 - Z(z)\, T(t)\right]^{\frac{1}{2}} dz. \tag{3}$$

In the above equation ϕ is known, and $Z(z)$ and $T(t)$ are unknown. There are two approaches to the problem of determining the time and space dependance of the electron distribution. One can assume that one knows $T(t)$, and solve the resulting integral equation for $Z(z)$. Or one can assume an arbitrary $Z(z)$ and solve for $T(t)$. It will be shown that for the given data, the <u>form</u> of the function $T(t)$ is practically independent of the space variation $Z(z)$.

From theoretical results it can be inferred that the actual spatial electron distribution is roughly sinusoidal in shape. Then one can consider the cases $Z =$ constant and $Z(z)$ having the form of a linear ramp to be limiting cases, with the actual distribution lying between them (see Fig. 1).

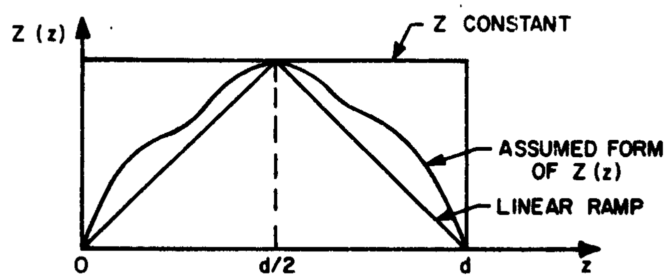

Fig. 1. The actual distribution (approximated by the curved line) lies between the two limiting cases.

It turns out that in these two limiting cases it is particularly simple to evaluate $T(t)$. In the case Z = constant,

$$\phi = \frac{\omega d}{c} - \frac{\omega}{c} \int_0^d (1 - T_c)^{\frac{1}{2}} dz \ , \tag{4}$$

where for simplicity the constant has been assumed equal to 1. Integration yields.

$$\phi = \frac{\omega d}{c} - \frac{\omega d}{c} (1 - T_c)^{\frac{1}{2}} \ ,$$

which is readily solved for $T_o(t)$:

$$T_c(t) = 2\psi - \psi^2 \ , \tag{5}$$

where ψ is the normalized phase shift

$$\psi = \frac{c}{\omega d}\,\phi \quad ,$$

and the subscript c denotes the fact that Z is constant.

There is no physical reason for assuming that the space distribution is not symmetrical. Thus if a ramp function is assumed for $Z(z)$, i.e.,

$$Z(z) = \frac{2z}{d}, \quad 0 \leq z \leq \frac{d}{2}, \tag{6}$$

then

$$\psi = 1 - \frac{2}{d}\int_0^{\frac{d}{2}} \left(1 - \frac{2z}{d}\,T\right)^{\frac{1}{2}} dz.$$

Upon integration,

$$\psi = 1 + \frac{2}{3}\,\frac{1}{T}\left[(1 - T)^{\frac{3}{2}} - 1\right] \quad .$$

Rearranging and squaring, one has

$$T^3 + \left[\frac{9}{4}(\psi - 1)^2 - 3\right]T^2 + 3\,\psi T = 0 \quad .$$

Solving for T_r and retaining only the solution that has physical significance, one has finally

$$T_r(t) = A - \sqrt{A^2 - 3\psi} \tag{7}$$

where

$$A = \frac{3}{8}\,(1 + 6\psi - 3\psi^2) \quad .$$

The function T(t) was evaluated in a number of cases. In each case, a set of data, consisting of pairs of values of t and ϕ, was plotted in the form of a smooth curve. Smoothed values of ϕ (in most cases no different from the experimental values) were taken from the curve. T(t) was then calculated for both the constant-Z assumption and the ramp hypothesis. The two curves were plotted on the same sheet of graph paper, and in every case the shapes of the two curves resembled each other so closely that it was impossible to distinguish them by eye. This being the case, it is evident that the data taken can give no information about the function Z(z), since no matter what form is assumed for Z(z), the time dependence T(t) has the same character.

It is possible however to determine the area under the curve Z vs. z, since at $t = 0$, $T(t)$ must be equal to unity. Since it is impossible to determine the exact shape of the transverse distribution $Z(z)$ anyway, it is illuminating to assume a form for $Z(z)$ that is easy to work with and such that the area that it satisfies the initial condition $T(0) = 1$.

The simplest functional form for $Z(z)$ from the point of view of evaluating the phase integral is a trapezoid (see Fig. 2). The trapezoid that will be used is symmetrical about $z = d/2$, has height 1, is d cm. wide at the base and d-d' cm. wide at the top. It is evident that by adjusting the break points $d'/2$ and $d - d'/2$ the trapezoid can be made to approximate any function from a rectangle to a triangle, i.e., it can be made to enclose any desired area.

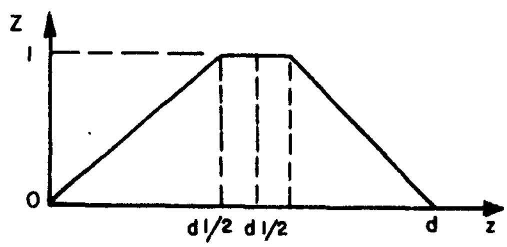

Fig. 2. Any distribution can be approximated by a trapezoid.

For the trapezoidal distribution of Fig. 2,

$$\psi = 1 - \frac{2}{d}\int_0^{\frac{d'}{2}} \left(1 - \frac{2z}{d'} T\right)^{\frac{1}{2}} dz - \frac{2}{d}\int_{\frac{d'}{2}}^{\frac{d}{2}} (1 - T)^{\frac{1}{2}} dz. \tag{8}$$

After integrating, one has

$$\psi = 1 + \frac{2}{3}\frac{d'}{d}\frac{1}{T}\left[(1 - T)^{\frac{3}{2}} - 1\right] - \frac{d - d'}{d}(1 - T)^{\frac{1}{2}}. \tag{9}$$

Rearranging terms and squaring gives

$$(3 - D)^2 T^2 + 3(D^2 - 2D - 3T_c)T + 12\,\psi D = 0$$

where

$$D = \frac{d'}{d}, \quad T_c = 2\psi - \psi^2 .$$

The solution is

$$T = A \pm \sqrt{A^2 - B}, \tag{10}$$

where

$$A = \frac{3(3T_c + 2D - D^2)}{2(3 - D)^2}, \quad B = \frac{12\psi D}{(3 - D)^2}.$$

When T is plotted for $0 < D < 1$, it is found that the curve lies between the curves for the constant case (T_c) and the ramp. The value of D that should be used is that value that makes $T(0) = 1$. If in equation (9) one sets $T = 1$ and solves for $D = d'/d$, the result is

$$D = \frac{3}{2}\left[1 - \psi(0)\right], \tag{11}$$

where $\psi(0)$ is the value of ψ at $t = 0$.

A word is necessary about the sign in equation (10). For all values of ψ greater than $D/3$, take the larger root of the quadratic (use the plus sign in equation (10). For all values of ψ smaller than $D/3$, take the smaller root (use the minus sign).

Of course the function ω_p/ω^2 may not be separable into functions of time and position alone, and, in fact, probably is not separable. That is, the spatial electron distribution may change continuously with time. The electrons in the center of the tube may "decay" at a faster rate than those at the walls, or vice versa. However, just as the data contains no information regarding the spatial distribution Z(z), so it tells nothing about how the spatial distribution might be changing with time.

It is also apparent that two or more different distributions can give rise to the same time dependence T(t).[1] For instance, assuming either of the two configurations shown on (Fig. 3), the same data ϕ (t) will yield the same time dependence T(t). Thus while the data tells a great deal about the rate of decay, it tells little about the spatial distribution.

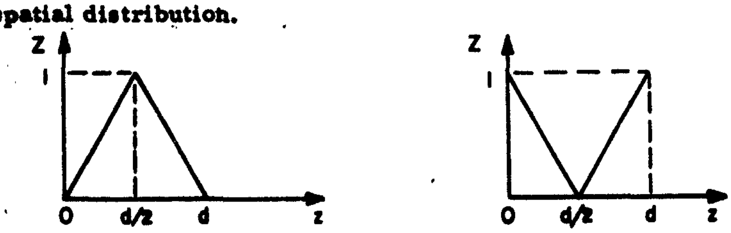

Fig. 3. If the two distributions decay at the same rate, the phase shift ϕ (t) will be identical in the two cases.

THE EFFECT OF COLLISIONS ON THE DECAY RATE

In what has been said so far, no account has been taken of collisions between electrons and neutral particles. It will be shown that, for a given set of data, $T(t)$ is smaller at small values of t, and larger at large values of t, when the effect of collisions is taken into account than it is when collisions are neglected. The two curves cross at the point $T(t) = \frac{\nu}{\omega}$.

Equation (1) gives the phase shift per unit length (for the plasma) in terms of the plasma frequency, which is proportional to the square root of the electron density, and also gives the attenuation constant in terms of the plasma frequency and the collision frequency. Whitmer[2] writes, "It can be seen that a measurement of the change in the phase of a wave transmitted through an ionized gas with respect to a reference path will yield n . By similarily measuring the attenuation, ν may be obtained .... [n is assumed uniform throughout the volume of the gas encompassed by the microwave horns] . Since the electron density that is measured is an average density over this volume, it is believed that this assumption does not introduce an appreciable error in the measurement." Thus in solving for ν, one must use that value of ω_p^2/ω^2 such that if n (and therefore ω_p^2/ω^2) were constant over the volume of the discharge tube, the phase shift produced would be equal to the observed phase shift ϕ. However to find ν one must first find α .

In performing the experiment the insertion loss L in db attenuation (dba) was also measured. By definition,

$$L = 10 \log_{10} \frac{P_1}{P_2} , \tag{12}$$

where P_1 is the transmitted power with no plasma in the tube and P_2 is the transmitted power with plasma present. With no plasma present, the attenuation in the reference signal was equal to that of the transmitted signal. When the plasma was introduced into the transmission path, the attenuation was again increased until the amplitudes were equal. Thus the attenuation added in the reference path is just L db.

But P_1/P_2 is simply $e^{2\alpha d}$, where d is the length of the discharge tube in the direction of propagation. Hence

$$L = 10 \log_{10} (e^{2\alpha d}) ,$$

or

$$a = \frac{.23}{2} \frac{L}{d} \quad .$$

Inserting the value d = 12 cm, one has finally that

$$a = .00958 \text{ L nepers/cm.} \tag{13}$$

Putting this value of a into equation (1) and solving for $\frac{\nu}{\omega}$, one sees that

$$\frac{\nu}{\omega} = .0916 \frac{(1 - T_c)^{\frac{1}{2}}}{T_c} \frac{L}{f} , \tag{14}$$

where L is db attenuation, f is frequency in Gc, and $T_c = 2\psi - \psi^2$ is the time dependence for uniform electron density. It is found that for f = 12.4 Gc, the average value of $\frac{\nu}{\omega}$ is .375 (L was not measured at any other frequencies). It is apparent then that the effect of collisions cannot be neglected.

Albini and Jahn[3] have examined quantitatively the effect of collisions on the phase of the transmission coefficient. They conclude, " The values of this phase can be estimated surprisingly well by a simple average of the propagation exponent over the ramp:

$$\phi_T = \phi_D - \text{Re}\left[\int_0^{z_0} k(z)\, dz\right] \quad . \text{"} \tag{15}$$

Consider again the trapezoidal fundtion Z of Fig. 2 . It is evident that if $d' \approx d$, as is indeed the case in all the examples considered, then Z may be regarded simply as a perturbation of a ramp function, and the results of Albini and Jahn are applicable. In this case $k^2 = -\gamma^2 = \frac{\omega^2}{c^2}\varepsilon'$ is complex, and ( ) becomes

$$\phi = \frac{\omega d}{c} - 2\text{Re} \int_0^{\frac{d'}{2}} K_1 (z)\, dz - 2 \text{ Re} \int_{\frac{d'}{2}}^{\frac{d}{2}} k_2 (z)\, dz \ ,$$

where $k_1 (z)$ and $k_2 (z)$ are the wave numbers for the ramp and the constant part of Z(z), respectively. Thus in general

$$k(z) = \frac{\omega}{c}\left[1 - \left(\frac{\omega_p}{\omega}\right)^2 - j\left(\frac{\omega_p}{\omega}\right)^2 \frac{\nu}{\omega}\right]^{\frac{1}{2}} \quad . \tag{16}$$

Over the ramp,

$$\left(\frac{\omega_p}{\omega}\right)^2 = \frac{2z}{d'} T ,$$

and on the constant portion,

$$\left(\frac{\omega_p}{\omega}\right)^2 = T .$$

Thus

$$\psi = \frac{c}{\omega d}\ \phi = 1 - \frac{2}{d}\ \mathrm{Re}\left\{\int_0^{\frac{d'}{2}} \left[1 - \frac{2z}{d'} - j\frac{2z}{d'}\ T\frac{\nu}{\omega}\right]^{\frac{1}{2}} dz\right\}$$

$$- \frac{2}{d}\,\mathrm{Re}\left\{\int_{\frac{d'}{2}}^{\frac{d}{2}} \left[1 - T - jT\ \frac{\nu}{\omega}\right]^{\frac{1}{2}} dz\right\} .$$

At this point it is convenient to introduce a new quantity

$$K = \left[1 - T - j\,T\ \frac{\nu}{\omega}\right]^{\frac{1}{2}} .$$

Writing $K = R - jI$, where R and $-I$ are the real and imaginary parts of K respectively, one finds that

$$R \approx (1 - T)^{\frac{1}{2}}$$

$$I \approx \frac{1}{2}\ \frac{\nu}{\omega}\ \frac{T}{(1 - T)^{\frac{1}{2}}} . \tag{17}$$

Hence

$$\left[1 - \frac{2z}{d'}\ T - j\ \frac{2z}{d'}\,T\ \frac{\nu}{\omega}\right] =$$

$$1 + \frac{2z}{d'}\ (1 - T) - \frac{2z}{d'} - j\ \frac{4z}{d'}(1 - T)^{\frac{1}{2}}\,\frac{1}{2}\ \frac{\nu}{\omega}\ \frac{T}{(1 - T)^{\frac{1}{2}}}$$

$$= \frac{2z}{d'}(R^2 - 2jRI - I^2) + 1 - \frac{2z}{d'} + \frac{1}{2}\ \frac{z}{d'}\left(\frac{\nu}{\omega}\right)^2\frac{T^2}{1 - T}$$

$$\approx 1 - \frac{2z}{d'}\ (1 - K^2) .$$

Therefore

$$\psi = 1 - \frac{2}{d}\ \mathrm{Re}\left\{\int_0^{\frac{d}{2}} \left[1 - \frac{2z}{d'}(1 - K^2)\right]^{\frac{1}{2}} dz\right\} - \frac{2}{d}\ \mathrm{Re}\left\{\int_{\frac{d'}{2}}^{\frac{d}{2}} K\,dz\right\} .$$

Carrying out the integration,

$$\psi = 1 - \mathrm{Re}\left\{\frac{2}{3}\,D\left(1 + \frac{K^2}{1 + K^2}\right)\right\} - \mathrm{Re}\left\{K\,(1 - D)\right\} ,$$

where, as before, $D = d'/d$. But

$$\mathrm{Re}\left(1 + \frac{K^2}{1+K}\right) = \frac{1 + 2R + 2R^2 + R^3 + I^2 R}{1 + 2R + R^2 + I^2}$$

$$= \frac{R\left[V + R + 2(1 - V)R^2 + 2R^3 + (1 + V)R^4\right]}{V + (1 - 2V)R^2 + 2R^3 + (1 + V)R^4}$$

where $V = \left(\frac{\nu}{2\omega}\right)^2$. Hence

$$\psi = 1 -$$

$$\frac{2}{3} D \frac{R\left[V + R + 2(1 - V)R^2 + 2R^3 + (1 + V)R^4\right]}{V + (1 - 2V)R^2 + 2R^3 + (1 + V)R^4} - R(1 - D) .$$

Rewriting the last equation in powers of R, one has

$$P(1 + V)R^5 - \left[\theta(1 + V) - 2P\right]R^4 + \left[2(3 - \theta) - P(1 + 2V)\right]R^3$$

$$-\left[\theta(1 - 2V) - 2(3 - P)\right]R^2 + VPR - V\theta = 0 , \qquad (18)$$

where

$$P = 3 - \frac{d'}{d} \qquad \theta = 3\left(1 - \frac{c}{\omega d}\,\theta\right)$$

$$V = \left(\frac{\nu}{2\omega}\right)^2 \qquad R = (1 - T)^{\frac{1}{2}} .$$

Since T is constrained to lie between 0 and 1, R is also, and thus it is necessary to find the root of equation (10) lying between 0 and 1 (there is only one). Horner's method and Bairstow's method were used to find R. It was found that the values of T, taking collisions into account, range from about 70% to about 120% of the corresponding values of T neglecting collisions (T is proportional to the electron density). Thus $\left(\frac{\omega_p}{\omega}\right)^2$ is always less than 1, i.e., there is no cut-off region, even at $t = 0$ when the plasma is densest.

EXPERIMENTAL METHOD

The experimental set-up is shown in Fig. 4.

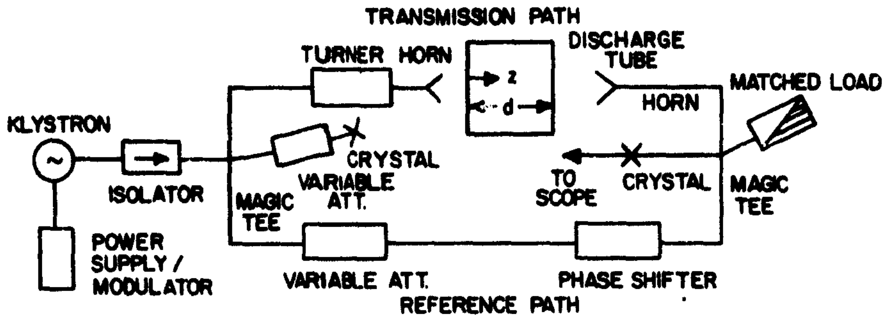

Fig. 4. Simplified block diagram of experimental set-up.

A pulsed dc glow discharge is maintained in the discharge tube, which contains hydrogen gas at a pressure of about 2 mm Hg. The discharge current is roughly proportional to the applied voltage. The electron density in the plasma reaches its maximum value when the current has decayed to half its peak value or less. In the period known as the " afterglow," that is, when the applied electric field is removed, the electron density decays gradually to zero.

The klystron is operated at a frequency ω slightly less than the maximum plasma frequency $\omega_{p\ max}$. At the first magic tee, the signal divides, half going through the transmission path and half through the reference path. Since the electrons in the plasma oscillate at approximately the same frequency as the microwave signal, they interact with the signal and affect its amplitude and phase. (Since the ions oscillate at a much lower freqency, their effect on the signal is negligible.) If now the variable attenuator and phase shifter in the reference path are adjusted so that the reference signal has the same amplitude as the transmitted signal and is 180° out of phase with it, the two signals will interfere destructively in the H-arm of the second magic tee and a null indication will be obtained at the output. However as the attenuator is varied the change in phase of the signal passing through it also varies significantly. If, in making a series of measurements, only the phase shifter is varied, then the detected output signal will be minimum when the transmitted and reference signals are exaxtly out of phase. This is the method used in the experiment in determining the phase of the transmitted signal.

As has been mentioned before, the klystron frequency must be somewhat less than the maximum plasma frequency. Furthermore, it is desirable that reflections from the glass walls of the discharge tube be kept as small as possible. For this reason, the frequency is chosen such that the thickness of the glass walls is an integral number of half-wavelengths. Then, with the attenuator in the reference path set at its maximum value and the attenuator in the E-plane arm of the first magic tee set at zero, the tuner in the transmission path is adjusted so that the signal in the E-pland arm is zero. Under these conditions, if the coupling between the H- and E-plane arms is small, the signal from the walls of the tube is negligible. This adjustment is made with no voltage applied to the discharge tube.

The method used for making the measurements is straightforward. The phase shifter and attenuator in the reference path are adjusted for null signal in the output arm of the magic tee in the absence of plasma. The discharge is then initiated, and the detected output signal is displayed on an oscilloscope. (See Fig. 5). The lower trace is present because the square wave modulating signal is not synchronized with the high-voltage pulses. Thus when a pulse appears, the klystron may be either on or off, producing an upper and a lower trace. The spacing between the traces is proportional to the square of the signal voltage. The applied pulse is used to trigger the horizontal sweep circuit. The time of appearance of the first fringe in the afterglow or decay region is taken as the origin of the time axis.

A point on the trailing edge of the last fringe is arbitrarily chosen and the corresponding time t is noted. The dielectric disc in the phase shifter is rotated, in the direction that causes the amplitude of the trace at time to to decrease, until a minimum is obtained, and the corresponding change in phase of the reference signal, considered as the positive increment ϕ, is recorded. A second point t, closer to the origin, is chosen, and the process is repeated. In each case ϕ is the total phase shift undergone by the reference signal; the phase shifter must always be rotated in the same direction. The process is continued until adjustment of the phase shifter causes no further observable change in the position of the minimum; this serves as an accurate check on the position of the time origin. If there is any discrepancy or ambiguity, the method just described should be used to fix the location of the origin.

ϕ is then plotted as a function of t, where t ranges from $+\infty$ (zero phase shift) to zero.

Since the phase shifter and attenuator are initially adjusted for zero interference signal in the absence of plasma, the change in phase ϕ at any time is simply the total phase shift through the empty tube, minus the total phase shift through the plasma. Thus ϕ is given by equations (2) and (3). The methods of the previous sections are then used to reduce the data and determine the rate of decay of the electron

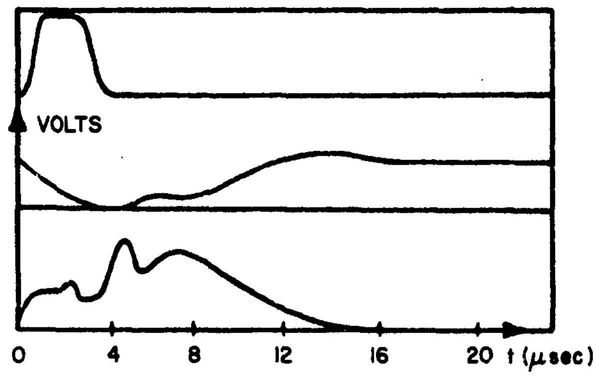

Fig. 5. Top to bottom: Discharge current, transmitted signal, interference signal (output of tee) with attenuator adjusted for null signal in the absence of plasma.

density in the tube.

To return to the equipment, it can be divided into four parts: the vacuum system, the hydrogen generator, the modulator, and the microwave interferometer. The operation of the interferometer has already been described. The vacuum system consists of a diffusion pump and a mechanical forepump designed to pump the tube down to a pressure of the order of 10^{-6} mm Hg. Provision was made for connecting an ionization gage to the system to measure the vacuum. A bellows valve seals the tube off when the gas is admitted into it.

The hydrogen generator consists of a hydrogen tank, the generator itself, and a thermocouple gage for measuring the gas pressure in the tube. The generator proper is a nickel tube sealed at one end and connected at the other end to the hydrogen line. To admit gas into the discharge tube the valves in the gas line are opened and a large current is passed through the nickel tube. The current heats the tube, making it porous, and the hydrogen then diffuses into the vacuum system. When the desired pressure is reached, the current is shut off and the valves are closed. The gage reads approximately twice the actual pressure when used with gydrogen; the actual pressure however can be determined from a calibration chart.

The modulator employs a thyratron and a pulse-forming network to generate high-voltage pulses of 4 microsecond duration. The modulator is triggered by an audio oscillator. At first a repetition rate of 200 pulses per second was used. However, it was found that the high-voltage pulses heated the tube excessively, permitting air to enter the tube. When this happened, the pressure rose and the characteristic blue color of the hydrogen glow discharge turned red and blue. Frequent arcing between the electrodes made it impossible to make measurements. The repetition rate was reduced to 80 pps, and the trouble disappeared. The peak discharge current was approximately 60 amperes.

The discharge tube is described in the Introduction.

In the plasma itself, the maximum electron density is approximately 1.9×10^{12} electrons per cubic centimeter; that is, the gas is approximately .00165% ionized. The maximum electron temperature is of the order of $50,000^{\circ}$K., and the ion temperature about 5000°K. The peak discharge current is approximately 60 amperes. The discharge tube containing the plasma is essentially a constant-voltage device. Using a similar discharge chamber, it was found that when the peak voltage E was 1500 volts, the peak current I was 2 amperes. When E was 1550 volts, I was 15 amperes; at 1620 volts, I was 65 amperes, and at 1700 volts, I exceeded 80 amperes.

A glow discharge in hydrogen has a characteristic bluish color, and is of more or less uniform intensity throughout the tube. The cathode dark space, the negative glow and the Faraday dark space are clearly visible at the cathode.

EXPERIMENTAL DATA AND RESULTS

Figs. 6 and 7 show the variation of the phase shift with time in four of the trials. Figs. 8 and 9, which are typical of all four trials, illustrate the fact that the time dependence or decay rate T(t) is for all purposes independent of the assumed spatial distribution Z(z). An exponential decay is plotted for comparison. Fig. 10 gives the decay rate for the four cases, neglecting collisions. Figs. 11 and 12 show the decay process when the effect of collisions is taken into account. Fig. 13 compares the decay processes with and without collisions. In Figs. 14 and 15 are reproduced two of the experimental curves obtained by Ettenberg, Mentzoni and Tamir.[4]

It can be seen that the curves for the different trials are all very much alike, indicating that the data is probably fairly reliable.

Thus the purpose of the experiment, to determine the electron decay rate in a gas discharge, has been achieved. It has been found that the electron density decays roughly exponentially with time, and that the observed departure from exponential behavior can be explained by postulating the build up of ions on the walls of the discharge tube when the ionizing voltage is applied, or, by the presence of impurity atoms. It must be emphasized, however, that owing to the large amounts of impurities present in the discharge chamber and to the meagerness of the data obtained, very little can be inferred regarding the nature of the decay process and the explanation cited above must be regarded as speculation.

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